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Published in:
Proceedings of Indoor Air 2011

Publication date:
2011

Document Version
Early version, also known as pre-print

Evaluation methods for long term indoor environmental quality

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SUMMARY
In existing and future buildings there will be a lot of focus on energy uses and indoor environmental quality. Even if buildings are using several different kinds of energy sources the yearly energy performance is expressed in one format either as primary energy or CO_2 emission. As a consequence, in order to compare energy performance with the corresponding indoor environmental performance, there is a need to express also the indoor environmental performance on a yearly basis, referring both to each separate environmental factor (thermal comfort, air quality, light and noise) and to a combination of these factors. If the indoor environmental criteria in existing standards have to be met 100% of the time of occupancy, the amount of heating, cooling and/or ventilation capacity of any HVAC installation would be prohibitive in terms of energy consumptions. Economic and/or environmental considerations lead to a more pragmatic position of allowing the indoor environmental conditions to exceed the recommended ranges for a limited time: this can be verified both by computer simulations (design stage) and by the field monitoring (post-occupancy phase).

The present paper will present some concepts to carry out a whole year performance evaluation of the indoor environment, inspired by ISO EN 7730 (thermal environment) or EN15251 (thermal, indoor air quality, light and noise). Besides some new suggested concepts is tested. Based on data from indoor environmental measurements in an existing building, methods for long term evaluations will be presented and discussed. The results show that the different concepts to a great extend will bring the same relative results. The results also show that we today still do not have enough knowledge to be able to combine the indoor environmental parameters into "one number".

IMPLICATIONS
This topic is very relevant for the ongoing discussion on energy performance contra indoor environmental performance in buildings. If we are not express the yearly performance of the indoor environment in an understandable, synthetic and clear way we may risk to lose focus on the indoor environment compared to energy performance.

KEYWORDS
Indoor environment, criteria, measurements, comfort, air quality.

INTRODUCTION
The environmental factors that constitute the indoor environment are: thermal comfort, indoor air quality, acoustic and illumination. This makes it almost impossible to describe the indoor environment in a building on a yearly basis with only one value. This is much easier with energy, where the different energy carriers (electricity, fuel etc) can be converted to primary energy or CO2 emission. For the individual indoor environmental factors it is even not any standardized method for estimation of a yearly performance value.

Criteria for acceptable thermal conditions are specified as requirements for general thermal comfort (PMV-PPD or operative temperature, air velocity, humidity) and local thermal discomfort (draught, vertical air temperature differences, radiant temperature asymmetry, surface temperature of the floor). Such requirements can be found in existing standards and guidelines like EN ISO 7730 (2007), CR 1752 (1998) and ASHRAE 55 (2007). For free running or natural ventilated office buildings the criteria for an acceptable operative temperature are given as a function of the mean outdoor temperature (EN15251, ASHRAE-55).

Different categories of criteria, according to ISO EN 7730 (2005) and EN 15251 (2007), may be used depending on type of building, type of occupants, type of climate and national differences (Table 1). These standards specify several different categories of indoor environment which could be selected for the space to be conditioned. These different categories may also be used to give an overall, yearly evaluation of the indoor environment by estimation (measured, simulations) the percentage of time in each category.

If thermal comfort criteria have to be met 100% of the time of occupancy, including extreme weather conditions, the heating and/or cooling capacity of any HVAC installation would be prohibitive. Economic and/or environmental considerations lead to a more pragmatic position of allowing the thermal conditions to exceed the recommended ranges for a limited time. There is a need to quantify with some index long term comfort conditions to compare alternative designs and long term measurements in existing buildings during the post-occupancy phase.

Table 1. Example criteria for PMV-PPD, operative temperature and ventilation (CO_2) for typical spaces with sedentary activity. (EN15251, 2007)

Class	Thermal Comfort requirements		Operative Temperature range		Ventilation
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met	CO_2 Above outdoor
	[%]	[/]	[°C]	[°C]	[ppm]
I	< 6	-0.2 < PMV < + 0.2	21.0-23.0	23.5-25.5	350
II	< 10	-0.5 < PMV < + 0.5	20.0-24.0	23.0-26.0	500
III	< 15	-0.7 <PMV < + 0.7	19.0-25.0	22.0-27.0	800
IV	> 15	PMV > $\pm$ 0.7	< 19.0-25.0<	<22.0-27.0<	800<

Note: In standards like EN ISO 7730, EN15251 and EN 13779 (2007) categories or classes are also used; but may be named different (A, B, C or 1, 2, 3 etc.).

The use of categories during the design stage to evaluate different design options can be done by yearly computer energy simulations. In these calculations, the categories may be clearly adopted and the performance can then be expressed as percentage of time the indoor environment falls into the different categories. The use of categories to evaluate the indoor environment during operation of buildings based on measurements is more difficult. Focusing on the thermal environment assessed by in-field measurements, the use of PMV can highlight significant problems in the accuracy of the prediction (for example, the accuracy by evaluation of the clothing and activity is not good enough to estimate the difference between classes of PMV). But if it is decided that the evaluation is simplified referring only to the operative temperature, the major problem is the accuracy of the measurement of mean radiant temperature, which often is higher than 0.5 -1.0 K. For many buildings the difference between air and mean radiant temperature is however less than 2 K, and then this accuracy will not be so important.

The present paper deals with thermal environment and indoor air quality assessment. Based on data from measurements in an existing office building different methods for long term thermal comfort investigation are presented and discussed.

METHODS

In order to carry out a critical analysis on the use of the comfort categories as introduced by the standard EN 15251, a case study is here proposed and discussed.

The case study is a bank in Denmark (Lat: 55.5°, Lon: 9.75°,). The building shows a complex shape; from the architectural point of view a key elements is the roof shape, accommodating multiple functions. 83 prism-like skylights compose the spectacular roof surface defining the geometry of the building. A bookshop, a café, a real estate agent and the cash desk are placed at the ground floor level, around a central plaza. The working areas (basically open space offices) are mainly located on three open terraces, called "plateau", internally connected by broad staircases. On each floor also single offices, meeting rooms and other rooms for dedicated services are placed. The building envelope is made mainly by structural glass, with transmittance U=1.1 W/m^{2}K, and with the transmission coefficient (visible light/solar energy) equal to 0.64/0.35. The office is normally occupied during daily time from 8:00 to 18:00, from Monday to Friday.

The monitoring campaign in to the building started in July 2010 and it is currently running. In this paper, the data collected from July to December are shown. During that period, measurements of air temperature and CO_2 concentration were collected every 10 minutes in 12 different rooms, 4 at each floor. Meanwhile, an external climatic station collected data about the outdoor air temperature, relative humidity, wind velocity/directions and solar irradiance. The average monthly outdoor climatic data during the occupancy hours are shown in table 1.

Table 1. Average monthly outdoor climatic data monitored during the occupancy hours.

Month	Solar radiation [W/m²]	Outside Temperature [°C]	Relative Humidity [%]	Wind Velocity [m/s]	Mean degree direction
July	434	22,2	56	1,6	202
August	314	18,9	69	2,2	225
September	238	15,3	72	2,8	202
October	126	10,7	77	2,4	192
November	52	4,5	81	3,3	214
December	51	-2,4	83	2,1	218

The indoor environmental control of the building is divided into two main strategies:

- Type1: Embedded, water based radiant system for thermal control. Natural ventilation by controlled window openings to provide acceptable indoor air quality. This kind of strategy is applied in all the large spaces, like in the offices situated on the terraces, in the canteen and in the central plaza at the ground floor.
- Type 2: Convectors and balanced mechanical ventilation for heating during the winter period and an all-air HVAC system for cooling and ventilation control during summer. This kind of strategy is mainly applied in single offices and meeting rooms.

RESULTS

In this paper, for brevity reasons, the investigation focuses on two spaces. The first is an open space office located at the first floor and characterized by control strategy type 1. The second space is a single office also located on the first floor, characterized by control strategy type 2.
The aim of this investigation is to show different method for describing the long term thermal comfort and indoor air quality. In the first method standard EN 15251 is used to describe the quality. Figure 1 show the thermal performance of the two rooms is shown in terms of percentage of time according to the four categories (corresponding to different temperature ranges) suggested by the standard both for winter and summer period; in this work the air temperature is taken as the reference instead of the operative temperature suggested by the standard (only air temperature is measured in this investigation).

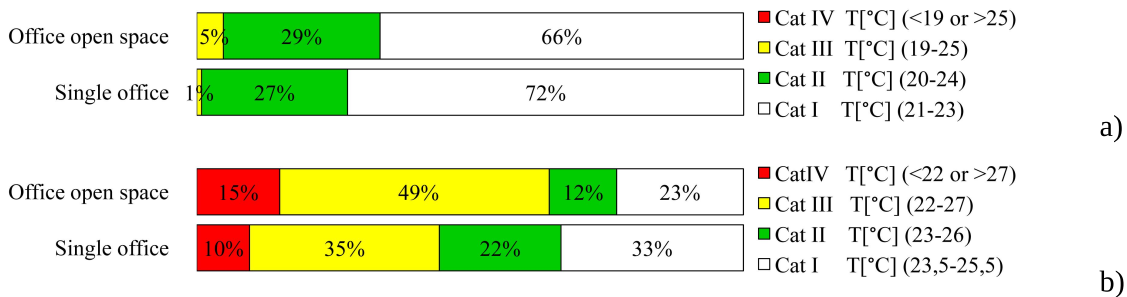

Figure 1. Indoor Thermal Quality expressed in percentage of time in four categories of the two analyzed rooms. Case a) Winter period. Case b) Summer period.

From Figure 1a it is possible to note that, during the heating period, both the two control strategies Type 1 and 2 are able to provide a very good thermal quality in the analyzed rooms. Only a little percentage of time (less than 5%) is in Category III, while more than the 66% of time the air temperature falls in Category I. The situation is different during the summer period. As shown in figure 1b, during the warm season the thermal quality in both the rooms presents a large percentage of time when the temperature falls in Category III and also 10-15% in Category IV.
The method is a fine way to present the results, but it does not allow to clarify the reason, and the problems, that determines a good or a bad thermal quality in the rooms because it does not shown any distribution of measured temperature. If we analyze the Category IV separating it in two parts, Category IV(-) when T<22°C and Category VI(+) T>27°C, it is possible to see that the percentage of time when the temperatures in the rooms exceeds the upper range is negligible. In the office open space during summer, the percentage of time (15%) when the temperatures are in Category IV is caused by space temperatures lower than 22°C. In the single office just the 0,5 % of the total percentage of time in Category IV (10%) is due to temperature values higher than 27°C. According to this analysis the performance in summer is not acceptable. The reason is too low space temperatures so by an optimized control this can be improved without any energy penalty.
The above evaluation was based on the requirements in EN15251 for mechanical cooled and ventilated buildings. The present building is however partly ventilated and cooled by natural ventilation. EN 15251 includes also criteria for the thermal environment for natural ventilated buildings based on the adaptive approach, where the recommended comfort interval is a function of the outside temperature (see figure 2). For this method the distribution of space temperatures in classes can also be used as shown in Figure 2 for the summer period. Using this kind of representation, it is interesting to analyse how the measured values are distributed and compare the situations of the two rooms.

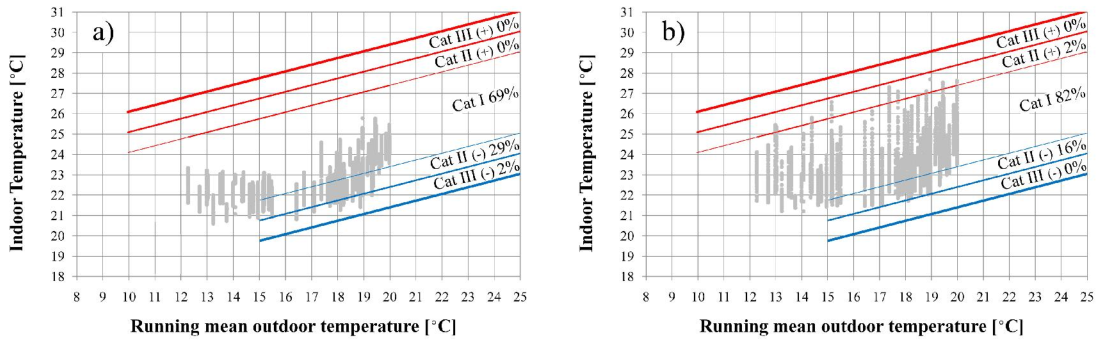

Figure 2. Values of indoor air temperature as a function of the exponentially-weighted running mean of the outdoor temperature during the summer period. a) Office open space. b) Single office.

The comparison between the two rooms shows that in the single office (Figure 2b), where there is the HVAC system, the indoor temperature distribution is more independent from the outside temperature than in the open space office (Figure 2a), that it is naturally ventilated. Looking at this graph and the values in Table 1, it can be observed that most of the time the outside temperature is lower than the indoor temperature, so the natural ventilation can be a useful and economic way to control the heating loads during summer. Moreover Figure 3 highlight that in both the rooms most of the temperatures are in the lower part of the acceptability range shown in Figure 2b): in summer, rooms falls into categories III and IV mostly due to under-temperatures, problem that can be overcome through a more accurate energy management of the building.
The indoor air quality can be expressed in a similar way by showing the percentage of time in the different categories (Table 1). Figure 3 shows that for both seasons the air quality, in terms of CO_2 concentration, is very good in the office open space and it is quite good also in the single office, where the percentage of time when the air quality is in Category I is always greater than 80%.

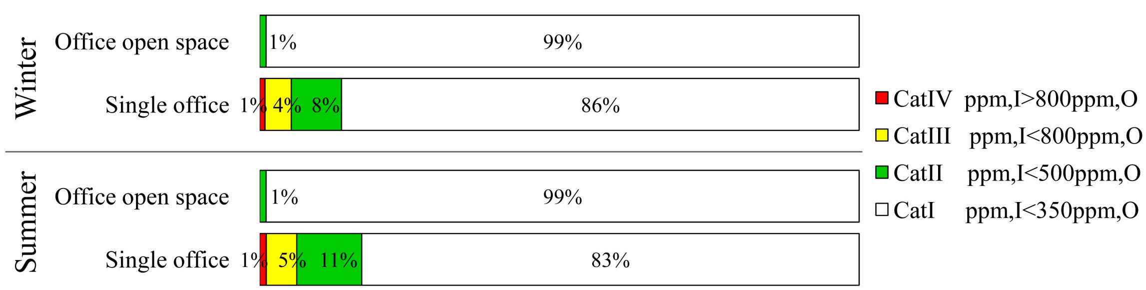

Figure 3. CO_2 concentration above outdoor expressed in percentage of time in four categories of the two analyzed rooms, in winter and in summer period.

Despite the good results, Figure 3 shows that in the single office that is mechanically ventilated by an HVAC system the air quality is worse than in the naturally ventilated room. This fact highlight that in this building the natural ventilation does not just have positive effect in summer period for the cooling loads control, as already said before, but can also guarantee an high air quality level during the whole year.

Another method to represent the measured data over a longer period is to calculate the deviations from the optimal indoor temperature to both the warm and the cool side. Using the PMV-PPD method for mechanical controlled buildings the optimal room temperature in winter is 22°C and in Summer 24.5°C. The deviation is calculated as degree hours above and below the optimal temperature. The results are shown in Figure 4.

Optimal temperature		24,5°C				22°C			
Period of time		Summer	Jul	Aug	Sep	Winter	Oct	Nov	Dec
Single office	Deg*h (-)	826	135	318	372	20	3	12	5
	Deg*h (+)	92	74	12	6	435	196	93	145
Open space office	Deg*h (-)	1099	171	435	493	8	7	1	0
	Deg*h (+)	26	26	0	0	533	152	120	261

Figure 4. Calculated deviations from the optimal room temperature as degree hours.

This method of representing the data show that in summer the temperatures are on the cool side and in winter they are on the warm side. This indicates less cooling should be applied in summer and less heating in winter. This representation of the data show overall the same trend as the other way of representing the data; but it is more detailed and give a better basis for analysis.

DISCUSSION AND CONCLUSIONS

The main idea behind the categories is to use them from the design up to the post-occupancy phase of buildings and HVAC systems, in order to provide evaluations about the indoor environment over a longer period like a year. The intention is not to force the operation of a building within one class the whole year, but to critically analyse the possible change of classes over the year. In fact, even if a building is designed for a lower category, it will still be possible to operate the building the majority of the year in a higher category. For building with HVAC systems the categories are based on different levels of the PMV-PPD index and/or operative temperature. If the long term evaluation also will be used to analyse a problem and find solutions it is important to evaluate the deviations outside the categories on the warm and cold side separately. In practice, very often, operative temperature is the reference parameter used in field investigations. It is, however, questionable if fixed temperature ranges should be used for a long term evaluation. In fact, people often adapt their clothing according to the outside climate: this is true for both mechanical and naturally ventilated buildings. This aspect needs to be deeper studied in future researches, in order to take this into account for category range definition.

A method to integrate the thermal environment and indoor air quality is still to be defined.

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